GLOBAL INTEROPERABILITY OF HIGH DEFINITION VIDEO STREAMS VIA ACTS AND INTELSAT

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ABSTRACT
In 1993, a proposal at the Japan-U.S. Cooperation in Space Program Workshop lead to a subsequent series of satellite communications experiments and demonstrations, under the title *of Trans-Pacific High Data Rate Satellite Communications Experiments*. The first of which is a joint collaboration between government and industry teams in the United States and Japan that successfully demonstrated distributed high definition video (HDV) post-production on a global scale using a combination of high data rate satellites and terrestrial fiber optic asynchronous transfer mode (ATM) networks. The HDV experiment is the first GIBN experiment to establish a dual-hop broadband satellite link for the transmission of digital HDV over ATM.

This paper describes the team's effort in using the NASA Advanced Communications Technology Satellite (ACTS) at rates up to OC-3 (155 Mbps) between Los Angeles and Honolulu, and using Intelsat at rates up to DS-3 (45 Mbps) between Kapolei and Tokyo, with which HDV source material was transmitted between Sony Pictures High Definition Center (SPHDC) in Los Angeles and Sony Visual Communication Center (VCC) in Shinagawa, Tokyo. The global-scale connection also used terrestrial networks in Japan, the States of Hawaii and California.

The 1.2 Gbps digital HDV stream was compressed down to 22.5 Mbps using a proprietary Mitsubishi MPEG-2 codec that was ATM AAL-5 compatible. The codec employed four-way parallel processing. Improved versions of the codec are now commercially available. The successful post-production activity performed in Tokyo with a HDV clip transmitted from Los Angeles was predicated on the seamless interoperation of all the equipment between the sites, and was an exciting example in deploying a global-scale information infrastructure involving a combination of broadband satellites and terrestrial fiber optic networks. Correlation of atmospheric effects with cell loss, codec drop-out, and picture quality were made.

Current efforts in the Trans-Pacific series plan to examine the use of Internet Protocol (IP)-related technologies over such an infrastructure. The use of IP allows the general public to be an integral part of the exciting activities, helps to examine issues in constructing the solar-system internet, and affords an opportunity to tap the research results from the (reliable) multicast and distributed systems communities. The current Trans-Pacific projects, including remote astronomy and digital library (visible human) are briefly described.

1. INTRODUCTION

A series of satellite communications experiments and demonstrations involving a combination of broadband satellites and terrestrial fiber optic networks was proposed in the Japan-U.S. Cooperation in Space Program (later renamed the Japan-U.S. Science, Technology and Space Applications Program) in 1993. The experiments and demonstrations were initiated in 1996 by the Japan-U.S. Science, Technology and Space Applications Program (JUSTSAP) as part of the G-7 Nations' Information Society - Global Interoperability of Broadband Networks (GIBN) project, with the High Definition Video (HDV) experiment being the first of the series [1].

In the United States, the GIBN project is coordinated by the White House National Economic Council, the National Science Foundation, and NASA. In Japan, the GIBN project is coordinated by the Ministry of Posts and Telecommunications and the Communications Research Laboratory. And in Canada by the Communications Research Centre (CRC) and by Teleglobe Incorporated.

The experiments and demonstrations are being carried out at various data rates up to OC-3 (155 Mbps), in order to develop and test the transmission techniques and protocols that are needed to incorporate satellite links in high performance global telecommunications networks. The Trans-Pacific series included high definition video, digital library, remote astronomy, tele-medicine, and tele-education and a number of other experiments and demonstrations.

In the HDV experiment, the teams in the United States and Japan demonstrated distributed high definition video (HDV) post-production on a global scale using a combination of high data rate satellites (Intelsat and NASA ACTS) and terrestrial fiber optic asynchronous transfer mode (ATM) networks. HDV source material was transmitted and composited in real-time between Sony Pictures High Definition Center (SPHDC) in Los Angeles and Sony Visual Communication Center (VCC) in Shinagawa, Tokyo, demonstrating that satellites can deliver digital image traffic at data rates up to OC-3 and with quality comparable to that of fiber optic cables [2, 3, 4].

The post-production-phase compositing process was performed in Tokyo on a green-screen HDV clip transmitted from Los Angeles. Test clips were also transmitted from Tokyo and Los Angeles and viewed on both sides in one-way or loop-back modes. The activities successfully demonstrated the global-scale infrastructure's feasibility in rapid transfer of HDV streams between remote shooting locations and post-production facilities. And when coupled with reliable multicast technology and digital cinema projection systems, the combination of broadband satellites and fiber optic networks help efficiently bring high definition virtual studios and digital theaters to locations never before possible. Additional Trans-Pacific experiments and demonstrations are being conducted and are briefly described.

2. THE PARTICIPANTS IN THE HDV EXPERIMENT

The Japanese participants of the HDV experiment included the Communications Research Laboratory (CRL), Japan Ministry of Posts and Telecommunications (MPT), Kokusai Denshin Denwa Company, Limited (KDD), Mitsubishi Electric Corporation, Nippon Telegraph and Telephone Corporation (NTT), and Sony Corporation; the U.S participants included Comsat, the George Washington University, GTE Hawaiian Tel, Japan-U.S. Science, Technology and Space Applications Program (JUSTSAP), Lockheed Martin, NASA Headquarters, NASA Glenn Research Center (GRC), NASA Research and Education Network (NREN), NASA Jet Propulsion Laboratory (JPL), Newbridge Networks Inc., Pacific Bell California Research and Education Network (CalREN), Pacific Space Center (Pac Space), Sony Picture High Definition Center (SPHDC), State of Hawaii, and Tripler Army Medical Center (TAMC). An international organization, Intelsat, also participated.

In the current phase of the Trans-Pacific experiments and demonstrations, we have added the following participants: AT&T Canada, BC Net (Canada), Canada's Communications Research Centre (CRC), Japan Gigabit Network, JSAT Corporation, Institute of Space and Astronautical Science (ISAS, Japan), Mt. Wilson Institute, NASA Goddard Space Flight Center, National Library of Medicine/National Institute of Health, NTT Communications, Sapporo Medical University, Soka High School, Thomas Jefferson High School, Teleglobe Incorporated, and University of Maryland.

3. NETWORK CONFIGURATION AND ATM ANALYZERS

The end-to-end path configuration of the experimental link is shown in Figure 1. A high data rate link between the U.S. and Japan was established by a combination of two broadband satellites and several terrestrial fiber optic networks [2].

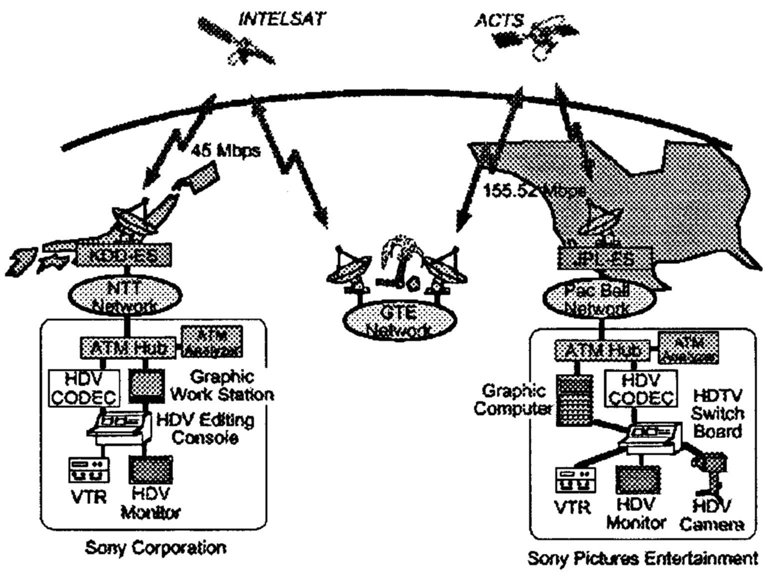

Figure 1, System Configuration of the Trans-Pacific High Definition Video Experiment.

On the Eastern Pacific, the NASA ACTS served to link the U.S. mainland and Hawaii. The satellite link operated at rates up to OC-3 (155 Mbps), and connected the fiber optic networks of GTE Hawaiian Tel and Pacific Bell CalREN. The various terrestrial facilities consisted of the GTE Hawaiian Tel network, Tripler Army Medical Center ACTS earth station, JPL ACTS earth station, Pacific Bell CalREN, and Sony Pictures High Definition Center in Culver City, California. The ATM switches used in the GTE Hawaiian Tel and Pacific Bell CalREN networks were manufactured by Newbridge, Cisco and Fore Systems. The ACTS terminal was constructed by Bolt Beranek and Newman Inc. (BBN), and the major components consisted of a 3.4 meter antenna made by Prodelin, digital terminal electronics made by BBN, and a 696 Mbps modem made by Motorola. The uplink frequency of 29.4 GHz and the downlink frequency of 19.6 GHz were used, and the terminals employed BPSK (binary phase-shift keying) modulation scheme and Reed-Solomon (232, 216) error correction code. The ACTS satellite was used in the bent-pipe mode using the Microwave Switch Matrix (MSM) during the experiment.

On the Western Pacific, the Intelsat 701 satellite served to link Tokyo to Hawaii at rates up to DS-3 (45 Mbps), and connected the fiber optic networks of KDD, NTT, and GTE Hawaiian Tel. The various terrestrial facilities consisted of the GTE Hawaiian Tel network, GTE Hawaiian Tel Kapolei Intelsat earth station, KDD Shinjuku Intelsat earth station, KDD and NTT ATM networks, and Sony Visual Communication Center (VCC) in Shinagawa, Tokyo. The ATM switches used in the KDD and NTT networks were manufactured by Fore, Lucent, and Fujitsu. Intelsat provided the use of its 701 satellite for the experiment, and the transponder was cross-strapped between Ku-band (towards Japan) and C-band (towards Hawaii). The uplink frequency was 14 GHz and the downlink frequency was 11 GHz on the Japan side; the uplink frequency was 6 GHz and the downlink frequency was 4 GHz towards the Hawaii side. The NEC/KDD modem used in the Intelsat earth station was a QPSK (quadrature phase-shift keying) modem with concatenated error correction code of 7/8 Viterbi and Reed-Solomon (255, 239), with bit interleaving to reduce cell loss.

Sony HDD-1000 recorders (VTR's) were used to play and record HDV. Sony HDC-500 High Definition CCD cameras were used to capture images for post-production processing. High definition video system monitors and projectors were used at both locations in console- or theatre-viewing of the images.

4. HIGH DEFINITION VIDEO AND BLUE/GREEN-SCREEN COMPOSITING

The high definition video equipment used conform to the Society of Motion Picture and Television Engineers (SMPTE) 240M-1994 formats [1]. It is a production system that matches or exceeds the quality of film while delivering the convenience of digital production and transmission. The format specifies 1035 active lines per frame and 1920 active samples per line (1035v x 1920h), with the aspect ratio of 16:9. The raw bit rate is 1.2 Gbps.

Blue/green-screen *compositing* is a process of recording subject images in front of an entirely blue or green background. The background may later be replaced in the post-production process with selected images to create the appearance of subjects being filmed in various locations or with special effects.

In the traditional way of film-making, performing blue/green-screen cinematography with photographic materials often takes weeks and many iterations between the director and the film laboratory to produce images matching the director's vision. The virtual studio concept demonstrated by the experiment would allow the post-production processing to be done in real-time and from locations not served by broadband terrestrial networks. The resulting video may then be viewed at remote locations using a portable HDV monitor. This made possible the instant review of compositing results and permitted the changes in remote HDV cinematography to the director's liking. The real-time post-production activities therefore significantly cut down on the amount of time needed for compositing, as well as shorten the length of time a cinematography team and props needs to be deployed at a remote location.

The HDV codec supplied by Mitsubishi Electric Corporation was a proprietary piece of equipment implementing a four-way parallel MPEG-2 processing for the SMPTE 240M/260M formats. Commercial versions of the codec are now available. The data rates generated by the codec can be selected from 22.5 Mbps, 60 Mbps, and 120 Mbps. The 22.5 Mbps mode was used in the experiment. The experimental codec had a small buffer, and therefore required strict timing synchronization to prevent overrun/underrun situations. An off-sync condition resulted from cell-loss affected the video in the way of frozen images (freeze-frame). There were no large, scrambled blocks or distorted audio as reported in other implementations [5,6]. In this way the codec robustly handled the cell-loss condition. The codec was interfaced to the Trans-Pacific network using ATM AAL-5 through a Cell Layer Assembly and Disassembly (CLAD) device. The MPEG-2 codec transformed the video stream into ATM cells for AAL-5. Typically, AAL-1 would be used compensate delay variation for constant-bit-rate (CBR) applications, but AAL-5 does not have such function. The experiment demonstrated that the Trans-Pacific satellite/terrestrial hybrid network provided a high quality link which did not require AAL-1 function to be used.

A part of the HDV post-production demonstration held involved green-screen cinematography performed at the SPHDC, the transmission of the images to Sony VCC in Japan for post-production processing, and the review of results at both locations.

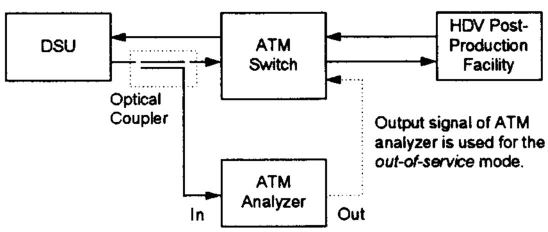

Figure 2, ATM monitoring system configuration.

5. ATM LINK PERFORMANCE

ATM link performance was measured using two Hewlett Packard 37717C ATM analyzers. A monitoring system was installed at each end point (Sony VCC and SPHDC) to measure the ATM layer transmission performance. Test cells were looped back from various points along the Trans-Pacific network.

The ATM monitoring system is shown in Figure 2. One such system was installed at each of the two end points in the Trans-Pacific infrastructure to measure ATM transmission performance. The ATM Hewlett Packard 37717C analyzer generated test cells and measured, in *out-of-service mode*, ATM layer items including cell loss, cell error, cell delay, HEC error SONET/SDH status. The end-to-end ATM test-cell results measured the performance of both the Intelsat and ACTS links.

The cell delay (CD) and cell delay variation (CDV) were shown in Table 1 were measured from SPHDC, which is reflected in those measured from Sony VCC. CD is the result of various equipment and link propagation delay, particularly over two satellite hops; CDV affects the quality of CBR services. The one-point (round-trip) CDV measured was always within 2μSec. The variation was about 6 cell-times in duration, but the jitter was not expected to affect most applications with sufficient memory buffers. The two-point (one-way) CDV measured was 0 μSec, with a round-trip-time of about 1.07 seconds, during a few hours of measurement in this mode. The measurements showed that the end-to-end link was very stable in terms of cell delay and variation performances.

Source	Loop-back point	Cell delay	Cell delay variation
SPHDC	TAMC earth station	555000 μs	2 μs
SPHDC	KDD earth station	1069547 μs	2 μs
SPHDC-JPL-GRC	TAMC earth station	555745 μs	2 μs

Table 1, Loop-back delays and variations measured from SPHDC. A connection was also set up between JPL and GRC, via NREN, to re-route test traffic during JPL ACTS earth station maintenance periods.

Date (U.S.)	Honolulu Weather	ACTS BER Log	ATM Tester Results
Mar 10 *Rain/Overcast Layer*	05:56-08:56pm PST 3000 ft few, 3500 ft few, 13000 ft broken, 23000 ft overcast. Rain showers in vicinity, south east.	No error for four hours. Bursts of errors in the last ten minutes of the experiment.	Looped back at Tripler, Hawaii. No error in 9.5×10^{8} cells (2 hr and 50 min). Cell loss ratio of 4.2×10^{-4} and error ratio of 1.9×10^{-5} for last 10 minutes.
Mar 18 *Broken Layer*	04:50-07:50pm PST 4000 ft scattered, 8500 ft broken - 4000 ft few.	No errors for two hours.	Looped back at Sony VCC. No error in 1.34×10^{8} cells.
Mar 20[1] *Broken Layers*	06:50-09:20pm PST 5500 ft broken, 7000 ft broken, 14000 ft broken, 23000 ft broken.	A few errors in a ten-minute block in the first hour. Otherwise, error-free.	Looped back at GTE, Honolulu. No error in one hour. Looped back at Sony VCC. No error in 10 minutes.
Mar 27 *Broken Layer*	06:50-09:50pm PST 3500 ft broken.	No errors in six hours.	Looped back at Sony VCC. One cell error in six hours.[2]

1. Most of the time used for end-to-end HDV transmission.
2. ATM tester used to monitor the end-to-end traffic.

Table 2, ACTS and ATM Performance.

The errors dominating the link were the result of rain attenuation of the Ka-band transmissions from Hawaii. Asymmetric performance was observed in the end-to-end link at times. The JPL-to-TAMC link generally ran error-free regardless of the weather condition in Los Angeles or Hawaii; the performance of the TAMC-to-JPL link depended highly on the weather condition in Hawaii. If it was overcast or raining in Hawaii, the error rate would generally be high. There would also be occasional link outages (Table 2).

The difference in link performances can be partially explained by the fact that the earth station antenna of the TAMC HDR has a very low elevation angle. Signals to Hawaii had to go through relatively thicker cloud layers or precipitation in this low elevation path. It needs to be noted that the ACTS satellite was originally designed to provide communications within the forty-eight contiguous states, but not to communicate with Hawaii. The steerable beam antenna had to be used in the Hawaiian link because the state is located outside the coverage of fixed-beam antennas. The satellite link margin was small with the steerable beam antenna, especially in Ka-band, which the signal underwent fading in rain. The experiment was also conducted in February and March, which are two of the wettest months in Honolulu[1].

The terrestrial fiber network did not contribute to the error statistics significantly. This result was consistent with the characteristics of satellite design and link frequency.

The ACTS HDR earth stations kept a log of the link status. The log files were updated every 10 minutes and included estimates of error rates before and after the Reed-Solomon decoder. The error rates were recorded in terms of the number of erroneous satellite cells (S-cell) in ten-minute intervals as detected by the Reed-Solomon decoder. Each S-cell contained 215 bytes of data and was about 1.03 ms in duration. According to Figure 3, about 70% of the time during the experiment the ACTS links were error free. And the S-cell error rate was approximately the same from 10^{-6} to 1.0.

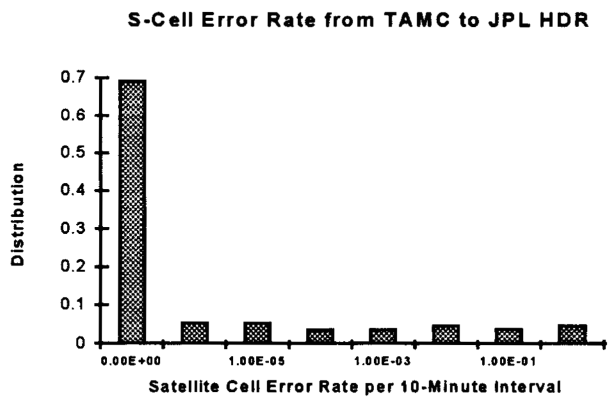

Figure 3, Histogram of ACTS S-cell error rate from the Tripler HDR to the JPL HDR terminal.

6. HDV PERFORMANCE

The experimental codec was originally designed for use with highly reliable terrestrial fiber optic networks. It had performed well in this experiment. Compared to the original uncompressed digital HDV source, the output of the video codec had no visible compression artifacts. In fact, in most instances the imperfections in the original source material were revealed. The only observable effect of the codec and the network was the occasional freeze-frame and/or silenced audio. A freeze-frame typically lasted around one second before the codec re-acquired the frame structure. There were no large, scrambled blocks or distorted audio as reported in other implementations [5,6]. In this manner the experimental device handled the cell-loss condition gracefully. It was observed that there were sporadic freeze-frames even when the codec was connected to an ATM switch in the loop-back mode. This effect was attributed primarily to the small buffer size and the occasional off-sync condition in the experimental implementation.

The observed HDV results drew parallel to those from the ATM monitoring system. When the weather in Hawaii was clear or had moderate cloud covers, the ACTS link generally ran error-free and the performance of the HDV was good. When it rained or when the cloud layer was thick in Honolulu, the ACTS link performance was poor and the HDV codec had a difficult time extracting frame synchronization information, resulting in many freeze-frames. Some of the freeze-frames could last several seconds as the ACTS link continued to be attenuated, particularly on the TAMC-to-JPL link.

7. CURRENT ACTIVITY

The Trans-Pacific High Data Rate (HDR) Satellite Communications Experiments included areas of high definition video post-production, remote astronomy, tele-medicine, tele-education, electronic commerce, and digital libraries [7, 8]. The experiments and demonstrations help explore and develop satellite transmission

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[1] The weather data used was obtained from the U.S. National Weather Service hourly observations. Average rainfall data, Honolulu, HI. October 1, 1949-January 31, 1997.

techniques, standards, and protocols in order to determine how best to incorporate satellite links with fiber optic cables to form high performance global telecommunications networks. Participants in these experiments will include the G7 countries, and other non-G7 countries will be invited as well.

At present time, the remote astronomy and visible human experiments are being carried out. The current phase of the experiments and demonstrations focuses on the use of Internet Protocol based technologies at rates up to OC-3 (155 Mbps). The technology also helps the participation of students and perhaps the general public.

The *Visible Human* experiment is the first step in prototype image database services over high-speed communications networks. A digital image library of volumetric data representing a complete, normal adult male and female cadaver. The thinly sliced images of cryosections that are derived from computerized tomography and magnetic resonance reside at the National Library of Medicine (NLM) in Maryland. The dataset is accessible by multiple nations. The current goal of this phase includes segmentation, classification, and three-dimensional rendering of the data set. Distributed processing will be conducted over the infrastructure.

The *Remote Astronomy* experiment aims to create a wide-area environment for distance learning and collaboration using Internet Protocol multicast and distributed file system. The experiment consists of collection of performance data and remote observation and control using multicast [9, 10] and distributed file access technologies. The application will establish a remote astronomy system using the Mt. Wilson 14" and 24" observational facilities from locations in North America and Japan. The initial use of the observatory will be scientists and students in the US and Japan, including Soka High School in Tokyo and Thomas Jefferson High School in Maryland. Wide area lectures, discussions and collaborations (post-processing) will be possible using a multicast teleconferencing system and distributed file system. The team has also developed a software ACTS link model for use with the Virtual InterNetwork Testbed for performance analysis purposes [11].

The capabilities afforded by an emerging global scale broadband information infrastructure emphasize the distributed nature of today's information systems. One such example is the solar system internet. These systems bring with it issues of scale, heterogeneity, robustness, and interoperability [12], and compose part of the questions the team will help address.

8. CONCLUSION

The Trans-Pacific High Definition Video Experiment tested the ability of satellites to carry high definition video signals for post-production processing between Sony studios in Tokyo and Los Angeles and successfully established an end-to-end Trans-Pacific link over two broadband satellites for streaming HDV traffic. The relatively good results obtained encourage the construction of a global information infrastructure utilizing broadband satellite systems.

The success of the HDV experiment demonstrated the feasibility of a global information infrastructure utilizing a combination of broadband satellites and terrestrial fiber optic networks. It is a result of seamless team work by an international group of participants, and also marked an exciting beginning for the GIBN Trans-Pacific High Data Rate (HDR) Satellite Communications Experiments. The team currently is carrying out new experiments and demonstrations using the Internet Protocol based technology [7, 8, 13]. The technology helps involve students and perhaps the general public in the exciting series of satellite communications experiments in the global information infrastructure, with results also applicable to the emerging solar system internet and next generation internet projects [14].

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